Geodynamic Investigations in Dronning Maud Land / Antarctica

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Introduction

The polar regions with their vast freshwater storage of the ice sheets in Antarctica and Greenland, which would supply enough water to rise the sea level globally by almost 70 m, are extremely sensitive to climate changes. Still, the contribution of these continental ice sheets is the major source of uncertainty, when estimating the change of the global sea level. For the last hundred years, the sea level rise has been estimated to be -0.2. . . 0.0 mm/yr for the Antarctic contribution, and 0.0. . . 0.1 mm/yr for the Greenlandic contribution. This uncertainty reflects also in the projection of the sea level change for the time period 1990-2100 – the figures are -0.17. . . 0.02 m for Antarctica, and -0.02. . . 0.09 m for Greenland (Houghton et al., 2001). Therefore, it is a major task to strengthen investigations of the polar ice sheets and their interactions with hydrosphere, atmosphere, and geosphere, especially concerning their dynamic reactions on time scales of 100 years (and below).
Geodesy with its modern observation techniques can provide measurements, which will help to constrain and validate investigations and model computations on the dynamics of the ice sheets. For many years, the Institut für Planetare Geodäsie has been carrying out geodetic research in Antarctica. Especially for one region in the Atlantic sector of Antarctica a huge variety of data have been collected, which form a comprehensive database for geodynamic and glaciologic applications.
This paper tries to give an overview on the long-term work of the Institut für Planetare Geodäsie and to highlight some results got so far. Many colleagues of the institute took part in carrying out these works – observation campaigns as well as analyses – or were responsible for the respective project, so it is not possible to acknowledge all of them by name. Instead, the reader's attention is called to the list of references.

Working Area

The working area is situated in Dronning Maud Land, in the Atlantic sector of Antarctica, and is approximately bounded by 7.5^o and 14^{o}E and 70^o and 72.5^{o}S, cf. Fig. 1. The open Lazarev Sea is blocked from the continent by the Nivlisen, a shelf ice of about 80 km north-south extension and mean thickness of about 250 m. The transition zone between the floating shelf ice and the grounded inland ice – the grounding zone – is interrupted by the Schirmacher Oasis, which extends over 25 km along the grounding line. Going further south the inland ice grows up to 1,200 m thickness. Huge alpine mountain chains form a barrier to the Wegener Inland Ice. These chains extend in west-east direction over hundreds of kilometres; Orvinfjella and Wohlthat Mountains form parts of these chains in the working area. A variety of glaciological and geological features were thoroughly investigated, cf. e.g. (Hermichen, 1995). Among others, intra-mountainous, ice-covered lakes can be found in the eastern part of the Wohlthat Mountains (Gruber Mountains). There, during the middle Pleistocene the ice surface level was about 1,000 m higher than at present. Since then, at least four glacial stages could be detected.

Due to the post-glacial warming, since the end of the last stadial (13 kyr BP), the ice surface decreased by 250 to 300 m. For the recent ice mass balance, the ablation and accumulation regime plays a major role. This regime shows a remarkable variation in the working area.

Phenomena Investigated

A variety of phenomena was investigated in the frame of several expeditions, which were mainly carried out during the Antarctic summer season. In the following, these investigations will be compiled, regarding the major observation techniques applied. Table 1 shows a comprehensive matrix of the respective phenomenon and relevant observation techniques.

Concerning *ice dynamics* one is interested in the velocity pattern of the inland ice as well as of the shelf ice, and also in possible causes. Along so-called traverses – tracks, which go from the Schirmacher Oasis for about 100 km across the ice, southwards to the Gruber Mountains ("Untersee Traverse") and to the Humboldt Mountains ("Insel Traverse"), northwards to the shelf ice ("North Traverse") – horizontal velocity vectors were determined (earlier by classic surveying methods, recently by GPS), cf. Fig. 1.
The determination of the horizontal velocity field could be extended into the area applying the technique of synthetic apperture radar (SAR) and carrying out an interferometric SAR analysis (InSAR). With SAR, not only the intensity (or backscatter energy) can be mapped, but also phase values can be acquired, thus enabling complex-valued data. From phase differences (between two scenes, provided a sufficient coherence) information on relative geometry changes can be infered. Whereas one interferogram gives the projection of the geometry change onto one direction, the combination of two interferograms of different orbit arcs enables the determination of the two-dimensional vector field. Hereby, the assumption of surface-parallel flow was adopted. From the interferometric analysis of SAR scenes of the ERS-1/2 tandem mission (cf. Fig. 1 for location of the scenes), the horizontal velocity vector field was determined (Dietrich et al., 1999). From this, the flow pattern of the Potsdam Glacier, which flows into the shelf ice north-east of the Schirmacher Oasis, can be nicely deduced. The highest velocity values are given in the centre of the glacier, close to the grounding line (about 100 m/yr). The results could be compared with the vectors determined by the terrestrial methods along the traverses. This comparison gave a rather good agreement (centimeter level), proving the high accuracy of the InSAR method (ibid). The deduction of the horizontal velocity field is not possible for regions, where large vertical deformations occur. These are regions, where the ice is not grounded – the shelf ice and the grounding zone. The grounding zone is visible in the interferograms by a strongly marked fringe belt. In order to get further insight into the nature of the vertical deformations, tidal dynamics were investigated.

Ocean tides could be determined, since at the northern edge of the Schirmacher Oasis several so-called epishelf lakes exist, which are connected to the ocean, so that the principle of communicating tubes works. Pressure tide gauge measurements were carried out in three of these lakes, with different observation periods. A combined analysis yielded the principal waves of the ocean tides (O1, K1, M2, S2) (Korth and Dietrich, 1996; Perlt et al., 2001).
In order to determine *Earth tides*, a gravimetric time series was recorded during the season 1994/95. For the four principal tidal waves, the comparison of the residual vectors with the ocean load vectors (computed on basis of the ocean tide model FES95.2) gave a good agreement, thus proving the validity of the tide model in this region (Dietrich et al., 1998).

The *tidal dynamics* of the shelf ice was further investigated by kinematic GPS. From kinematic point observations it was possible to determine shelf ice sites, where the ice is grounded (so-called "ice rumples") in contrast to the generally floating ice. In order to get a detailed insight into

the behaviour of the ice within the grounding zone, several kinematic GPS traverses crossing this zone were observed. These observations show the increasing damping of the ocean tide effect – which the free floating shelf ice follows perfectly – when approaching the grounding zone. Furthermore, it is possible to apply the elastic beam theory and to show, that the shelf ice behaves similar to an elastic plate which is fixed on one side (Korth et al., 2000; Perlt et al., 2001).
The location of the grounding zone is an important information for glaciological investigations (approximately given by blue line in Fig. 1). In order to get an idea of the temporal change of the grounding zone two different SAR interferograms were compared, whose acquisition times correspond to predicted times of high and low tide, resp. The tidal difference of about 150 cm corresponds to a horizontal shift of the grounding zone of about 5 km (Metzig et al., 2000). Thus, it was shown that the InSAR technique provides a powerful tool to investigate the location of the grounding zone, when additional information on ocean tides were complemented.

Coming back to the inland ice, a major parameter to be investigated is the ice mass balance. When measuring height changes (over a sufficient time basis) it is possible to infer the “specific mass balance”. Thereby, the measured height changes are transfered columnwise to a mass change, assuming a constant ice density profile with depth and integrating over the area. This approach is different to the determination of “surface mass balances”, which can be deduced when incorporating data on accumulation and ablation rates. Along the above mentioned traverses, repeated height measurements were carried out. Thereby, it is important to measure each epoch at the same position (which was ensured by geodetic techniques). From these measurement, the most remarkable result was infered for the “Untersee Traverse” (Schirmacher Oasis to Gruber Mountains), which crosses a large “blue ice” region (where ablation dominates). The determined decrease of ice surface heights corresponds to a negative specific mass balance of 10 to 15 cm/yr WE (Korth et al., 1999). Likewise, for the accumulation area (south

Table 1: Matrix of phenomena and observation techniques applicable for their investigation

phenomenon	*observation technique*					
	classic surveying	GPS (static, kinematic)	gravimetry (relative, tide series)	tide gauge	InSAR	radio echo sounding
ice dynamics	✗	✗			✗	
ocean tides		✗	✗	✗	✗	
solid earth tides			✗			
mass balance	✗	✗			✗	
geoid		✗	✗			
vertical crustal deformation		✗				
topography	✗	✗				✗
ice thickness						✗

of Schirmacher Oasis, “Insel Traverse”) it is more difficult to infer the specific mass balance, because the height change measurements are disturbed by large variations in the local accumulation.

Further geodetic and geodynamic features, which have been investigated, are the regional geoid and the vertical deformation pattern. A *regional geoid modelling* in the working area was possible, since a variety of additional data could be incorporated (gravity, ice surface heights, ice thicknesses). Method and results are described in detail in (Korth et al., 1997; Korth, 1998). The improved regional geoid yields an agreement with independently measured geoid heights (by GPS and tide gauge) in the centimeter level, in contrast to differences of some meters for global models (cf. ibid).
When searching for *vertical deformations* historical as well as recent ice mass changes have to be taken into consideration. Ice mass changes cause a response of the solid earth, whereby an immediate elastic effect (due to properties of the earth crust) can be distinguished from a long-term viscous effect (due to properties of the earth mantle). Despite the detailed data, which were described above or were inferred from glaciological investigations (Hermichen, 1995), regional data with a fine resolution are rare and/or of low reliability. For the working area, the postglacial rebound is given by model predictions with a maximum uplift of 1 mm/yr, while elastic response models give a subsidence of up to 2 mm/yr due to the applied accumulation scenarios. From GPS epoch campaigns, which were carried out during the seasons 1995/96 and 2000/01, the relative changes of the vertical positions of GPS sites in the Orvinfjella and Wohlthat Mountains with respect to a reference station in the Schirmacher Oasis were obtained (cf. Fig. 1 for location of GPS sites). The preliminary results give a first estimate of the sign of the vertical deformation relative to the reference station, and – regarding the accuracy (which is in the level of about 5 mm) – the order of magnitude: about 0 . . . +4 mm/yr. The vertical velocity of the reference station itself was analysed with respect to the geodetic reference frame ITRF97. Using data of the years 1995-2001, the estimation yields a vertical velocity of +6 mm/yr (with an accuracy of $\pm$4 mm/yr) (Rülke et al., 2001; Scheinert et al., 2001). More reliable statements will be possible, when a third observation campaign will be carried out after a reasonable time.

Résumé

In the region of Schirmacher Oasis, Dronning Maud Land, a variety of geodetic observation techniques were applied to investigate geodynamic phenomena.
Satellite aided techniques (Interferometric SAR) were combined with terrestrial methods (surveying, static and kinematic GPS) to infer ice dynamics, especially the horizontal velocity field of the inland ice and the dynamics of the shelf ice. Special attention was given to the location and migration of the grounding line. Observation of ocean tides as well as of earth tides allow a detailed explanation of major forcings to shelf ice dynamics.
Repeated GPS observations along traverses gave the opportunity to determine constraints on the specific mass balance, which is an important parameter for glaciological analyses. Using a variety of data a regional geoid improvement was carried out, thus determining an essential geodetic reference. GPS epoch observations were used to get a first insight on the vertical deformation in the working area.
It was shown, that only by combining various observation techniques – GPS, InSAR, classic surveying, gravimetry, tide gauge measurements – a comprehensive and detailed picture of the dynamics and interactions of ocean, ice and solid earth can be drawn. Nevertheless, these investigations have to be regarded only as a regional case study. However, it could be representative for a typical region of the Antarctic margin.
New, valuable data especially on the gravity field of the earth, but also for the investigation of the ice sheets, will be provided by future satellite missions (among others CHAMP, GRACE,

GOCE, ICESat/GLAS, CRYOSAT, ENVISAT). Nevertheless, it is very important to gain ground data of high accuracy to enable a validation of the satellite data to be provided. Using satellite data as well as airborne data (e.g. gravimetry, laser altimetry and radio echo sounding) it will be possible to investigate geodetic, geodynamic and glaciological features for extended regions in Antarctica.

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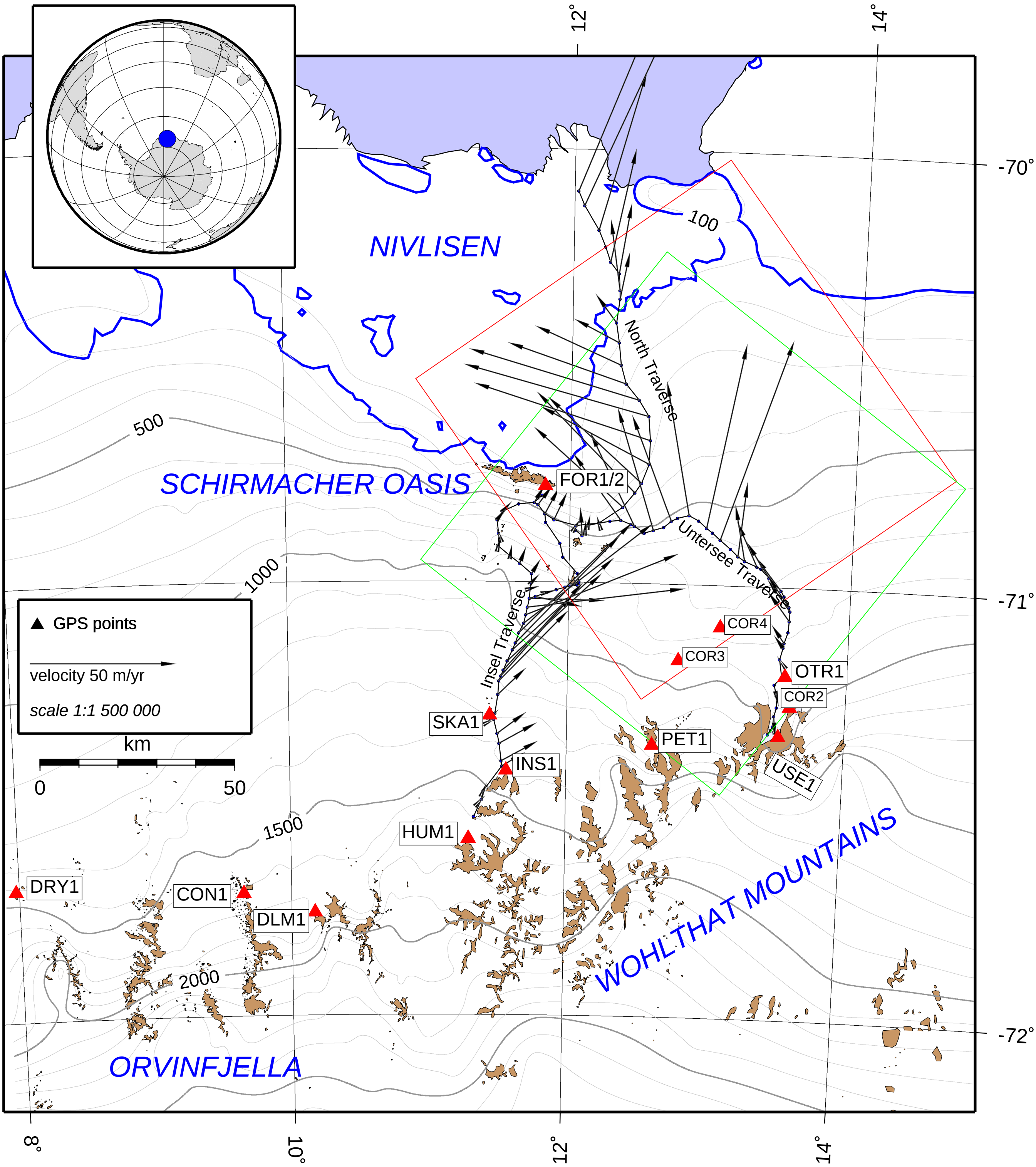

Figure 1: Overview of the working area in Dronning Maud Land.
The blue line gives the approximate location of the grounding line. GPS sites are marked by triangles. Along the traverses velocity vectors are drawn (see legend for scale). Quadratic outlines show the location of SAR scenes used for the interferometric analysis (red: ascending arc, frame 5715; green: descending arc, frame 5085). The location of corner reflectors is marked by the abbrevations COR2, COR3 and COR4.